DESIGN OF SOLAR HEATING SYSTEM COUPLED TO A GROUND HEAT STORAGE AND A GEOTHERMAL HEAT PUMP

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ABSTRACT

By 2020 all new buildings within the European Union should reach nearly zero energy level. Their energy needs should be significantly covered by renewable energy sources. As a consequence, it is important to identify which combinations of technologies will be suitable in order to reach such objectives. Climate conditions, final energy and investment costs, technological maturity and stakeholders' services quality are key elements for the final choice. This paper presents some results of a more general survey the purpose of which is to study different combinations of heating systems integrated in single-family dwellings under the Belgian climate conditions.

The heating system that is concerned is a solar heating system with a ground heat storage and a geothermal heat pump that exhibits energy performance in agreement with such future building standards. This system works with solar collectors which produce heat for space heating (SH) and domestic hot water preparation (DHW). This thermal energy is distributed to the building - using a short-term storage - when it is needed or stored in the DHW tank. If the production is in excess, the energy is stored into the ground using a borehole heat exchanger. This energy will then be used by a geothermal heat pump when the solar collectors cannot fulfil the building heating needs.

A design procedure has been developed and tested on several buildings using simulation tools. The borehole depth ranges from 150 m to 350 m and the solar collectors areas from 22 m^2 to 46 m^2 depending on the energy performance of the building. The procedure permits to reach a renewable coverage ratio higher than 80% (instead of 55% for solar heating coupled with a geothermal heat pump without storage). Results are presented for one building. The system performance is compared to that of a reference system (most likely to be used in practical case): air to water heat pump without any solar assistance.

INTRODUCTION

Improvement of the energy efficiency is the most cost-effective and fastest way both to increase security of energy supply and to reduce the greenhouse gases emissions responsible for climate change. In the EU, buildings represent about 40% of the final energy consumption. For residential houses, two thirds of this energy consumption is for space heating. Therefore, the reduction of energy consumption and the use of energy from renewable sources in the building sector are important measures for the European Union.

In May 2010, the EU recast the directive on the energy performance of buildings. In this directive [1], the European Commission proposes that Member States shall ensure that by 2020 all new buildings are Nearly Zero Energy Buildings (NZEB). NZEB means a building that requires a very low amount of energy so that it can be produced, to a very significant extent, by use of renewable sources (produced on-site or nearby the building). Member States shall transpose and precise these definitions in their own legislative system. Further information about the maximum allowable energy demand, the minimum coverage rate by renewable energy are indeed required. Considering the definition proposed by Torcellini, Pless and Deru [2], a ZEB (Zero Energy Building) produces on site at least as much energy as it uses in a year. There is no technological barrier to conceive a ZEB based on such a definition. However, economic considerations like investment and energy costs as well as climatic conditions and reliability of the stakeholders have to be taken into account at the national level. This is the reason why each Member State may adapt the concept of ZEB to NZEB (Nearly Zero Energy Building) to its own reality.

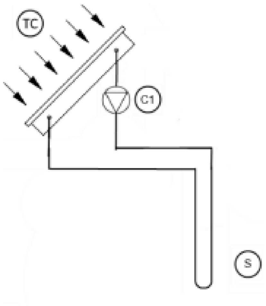
One of the main questions that arise when defining a NZEB is whether it is better to promote very low energy demand (passive houses) or high coverage by renewable energies in "just low energy buildings". Moreover, solar production is intermittent and often does not match building needs. Indeed, solar production occurs mainly during summer whereas most of the needs are in winter. This phase shift exists also between day and night. This appeals for the integration of heat storage technologies rising the complexity of the whole system.

It can be difficult to justify economically the use of such complex energy production systems in passive houses due to low absolute energy gains they lead to. Furthermore, the maximum required heat power is often less than a few kW in such dwellings and the heat demand for domestic hot water is often equal to the heat demand for space heating. These particularities require specific solutions (low power heat generators, high efficiency at both low and high production temperatures, new design procedures, adapted control strategy). Obviously, such solutions already exist: the PassivHaus Insitute reports that 33% of high performance buildings use integrated systems for heating and DHW production [3]. These integrated systems use solar collectors and a water tank to cover the energy needs of the buildings. Simulation may help to design such systems and to calculate their energy performance over one year. Such results may then be used for an economic analysis.

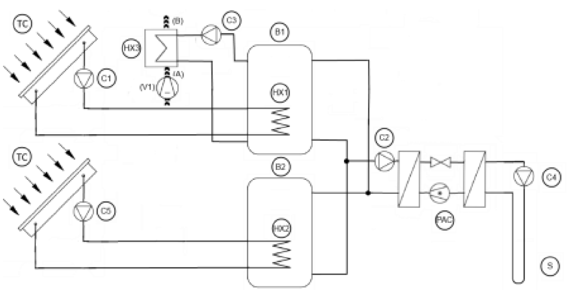
STUDY DESCRIPTION

System

The schematic diagram of the process is presented in Figure 1. Heat production is assured by thermal solar collectors (TC) and a heat pump (HP). There are two separate arrays of solar collectors. The first one is used to produce heat for space heating. It is connected to a long term heat storage (vertical ground heat exchanger (S)) as shown in Figure 1-a or to a short term energy storage (water buffer tank B1 thanks to heat exchanger HX1) as indicated in Figure 1-b. The second one is used for domestic hot water production (buffer tank B2 and heat exchanger HX2 in Figure 1-b).
During the summer period, the heat harvested by the first array of solar collectors is stored in the ground using the ground heat exchanger (Figure 1- a) whereas the second array of solar collectors produce heat for DHW production.



a- Long term storage of solar energy



b- Short term storage of solar energy +additional heat production using a HP

Figure 1: Schematics of the system

During the winter period, the solar heat that is produced by the first array of solar collectors is stored in the buffer tank (B1) to be used for space heating. If the temperature of this buffer tank is not sufficient, the heat pump is used for the extra heat production. The heat pump is used only if there is a heat demand from the building and if the temperature at the top of the water tank is below a set point value. The heat pump is of geothermal type and its evaporator is connected to the ground storage thanks to the same vertical heat exchanger as the one connected to the solar collectors. Its condenser is connected to buffer tank B1 but also to buffer tank B2 (DHW). The air-to-water heat exchanger (HX3) delivers warm air to the building. DHW needs are partially covered by the second array of solar collectors; the heat pump acts as a back-up system (as for space heating).

The fluid in the ground circuit is considered as a glycol-water solution (water-based liquid mixture and 35% of glycol) to prevent from the risk of freezing.

Method

The system has been designed - based on an a priori methodology – to fit the energy needs of a low energy one-family dwelling.

The first step design characteristics of the system as well as the building characteristics were then introduced in a simulation software (TRNSYS 17) to perform a one-year energy performance calculation [4]. TRNSYS is a software for simulating the dynamic thermal behavior of transient systems. It contains a general solver of sets of differential and algebraic equations which describe energy systems and buildings. It is based on a modular approach which enables the user to readily simulate a wide variety of systems. The software consists of component models (for collectors, controls, storages, heat exchangers, etc.) and an executive routine. In our study, the simulation time step is 10 minutes. Components models come from two sources: the

TRSNSYS standard models library and the TESS library.
The dwelling is modelled using TRNSYS's TYPE 56 with four distinct thermal zones. The weather-processing model uses standard TRNSYS TYPE 15 with the climate data file from Uccle (Belgium). The ground heat exchanger is modelled using TRNSYS's TYPE 557.

Simulation results consist in energy performance indicators (such as the fraction of the energy needs that is covered by renewables).

Analysis of the results based on the first step design methodology led to adapt some design characteristics and parameters. A trial and error procedure was adopted to refine the design. Main adapted parameters were the solar collector surface area and the total length of the ground coupled heat exchanger. Medium term annual ground temperature repeatability was the criterion that has been used for evaluating the pertinence of the final design. Results that are presented within this paper are based on the final design characteristics.

A parametric study has then been performed to have a better understanding of the influence of both the solar collector surface area and total length of the ground coupled heat exchanger on the whole system performance.

Duct ground heat storage model

The geothermal system is a vertical U pipe (diameter of 2.5 to 5 cm) made of high density polyethylene (HDPE) inserted in a vertical geothermal well (diameter of 12 to 15 cm, depth ranging generally from 20 to 200 m) as shown in Figure 2.

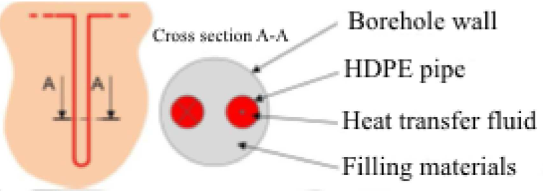


Figure 2: Schematic of duct ground heat storage

TYPE 557 modelled this system using the DST model (Duct ground heat STorage model) developed by Claesson et al [5]. The heat exchanger is supposed to be inserted in a storage volume which has the shape of a cylinder. The ducts are assumed to be uniformly placed within the storage volume. The model takes into account convective heat transfer in the fluid and conduction heat transfer in the ground. Temperature outside the storage volume is not affected by the heat storage or recovery. The solution to the problem of heat transfer in the ground is obtained by the superposition principle (additivity of partial solutions).
The first solution is obtained by the construction of several meshes each of which is a vertical section of a ground cylinder attributable to each U-tube. The second solution to the problem is achieved by the construction of a mesh representing the whole soil volume assigned to the geothermal heat exchanger and the surrounding ground. They are solved with use of the explicit finite difference method. Link equation between the two sub-systems has an analytical solution.

The storage volume is divided into a number of subregions which extend vertically and radially relative to the borehole center. Each subregion consists of the same geological material, so with the same properties: heat capacity of the surrounding ground and the heat transfer properties. Table 1 presents the main characteristics of the ground heat storage system considered in this study.

The local ground water flow may influence the thermal behavior of the ground heat storage. This influence depends on the number of fissures, their width, the extension of the fractured zones, and the local hydraulic gradients. These factors are very site-specific and a general statement about the influence of these on heat build-up is difficult to make. Moreover, different studies ([6], [7]) show that in most cases ground water flow has a minor impact on heat transfer. There are negelected in this study.

	Value	**Unit**
GROUND		
Storage volume	23550	m^3
Storage thermal conductivity	1,3	W/(m.K)
Storage heat capacity	2,65	MJ/(m^3.K)
BOREHOLES		
Number of boreholes	2	
Borehole depth	80	m
Header depth	1	m
Borehole radius	0,06	m
Fill thermal conductivity	0,7	W/(m.K)
U-TUBE PIPES		
Outer radius of U-tube pipe	0,025	m
Inner radius of U-tube pipe	0,023	m
Pipe thermal conductivity	0,42	W/(m.K)
FLUID		
Fluid specific heat	3,64	kJ/(kg.K)
Fluid density	1052	kg/m^3
Reference temperature	30	°C
Reference borehole flow rate	0,33	L/s

Table 1: Characteristics of DST

Heat pump

TYPE 927 was used to model this component (single-stage heat pump). This model is based on user-supplied data files containing catalog data for the heating capacity and power, based on the inlet load (secondary fluid at condenser inlet) and source (secondary fluid at evaporator inlet) temperatures.

In this study, the brine-to-water heat pump is selected in such a way that its heating capacity in standard conditions (B0°C/W30°C) fits the thermal needs of the building for an outdoor temperature of -5°C.

Solar collectors

The total surface area for space heating is calculated in such a way that the estimated solar heat production during summer period covers the space heating needs during the winter period.
The total surface area for domestic hot water is calculated in such a way that the estimated solar heat production covers the maximum of DHW needs during mid-season (April, May, October, November).

Both solar collector arrays are supposed to have a fixed tilt angle equal to 40° facing south. High efficiency flat-plate type solar collectors are used.

Their characteristics are presented in Table 2.

Total area for space heating	[m²]	25
Total area for space heating per building heated surface area	[m²/m²]	0.161
Total area for domestic hot water	[m²]	7.5
Zero loss collector efficiency (η_0)	[-]	0.806
Collector heat loss coefficient (a_1 / a_2)	[kJ/(h.m².K)] / [kJ/(h.m².K²)]	12.78 / 0.0468

Table 2: Technical characteristics of the solar collectors

Water tanks

Water tanks are modelled as stratified vertical and cylindrical water tanks with two inlets and two outlets as well as connections to an internal heat exchanger. All stratification nodes of the tank have a uniform size. Low thermal losses (1.2 kJ/(m².K.h)) are considered. Volumes are taken equal to 1000 liters for B1 and 200 liters for B2. Both water tanks are located inside the building.
Two internal heat exchangers are used for the solar circuit connection. Their overall heat transfer coefficient is equal to 165 W/(m².K).

Building main characteristics

76% of the Belgian people live in a single-family dwelling. The reference building that has been considered (presented in Table 3) is a single-family house of common type in Belgium new constructions but with energy performance that is higher than the national standards; the heat demand for space heating is 31.6kWh/(m².y) This house has a 155m² surface area living space, two floors and is occupied by a four-person family.

Location	Epinois (Belgium)
Structure	Wood
Insulation principle	Between-rafter
Inertia	Light
Building heated surface area [m²]	155
Windows area [m²]	21,2
Annual heating needs for space heating [kWh/(m².year)]	31,6
Maximum power for space heating [kW]	2,5
Annual heat needs for domestic hot water [kWh/(m².year)]	13,1
Transmission heat transfer coefficient [W/K]	45,9
Ventilation heat transfer coefficient [W/K]	27,1

Table 3: Building characteristics

Control strategy

The solar collectors are considered as the main heat generation system. Solar harvesting is activated for DHW production/short term storage for space heating if the difference between the temperatures downstream the solar collectors and the water temperature inside water tank B2/B1 (at the node located at HX2/HX1 outlet) is higher than 5°C.

The same temperature difference between water downstream the solar collectors and water inside the ground heat exchangers is needed to activate heat storage in the ground. Priority is given to short term storage during the heating season.

The heat pump does not take part to the storage process. It is activated only in case of heat demand from the building or in case of hot water demand provided that the set temperature is not reached at the water inlet of HX3 for space heating (35°C) or at the top of B2 (45°C) for domestic hot water supply.

Warm air circulation through HX3 is allowed when inside ambient temperature is lower than 18°C and is stopped when it is higher than 21°C.

Domestic hot water tapping program is inspired by Belgian regulations [8] (Figure 3).

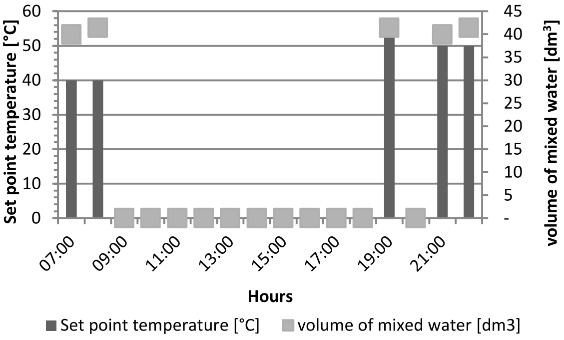


Figure 3: Tapping program

RESULTS

Solar energy production and storage

Figure 4 presents the solar energy that is produced and stored in the ground (Q_{solar_stock}), in B1 (Q_{solar_SH}) or in B2 (Q_{solar_DHW}) as a function of time. Two periods may be identified. During mid-season and winter, heat is stored in B1 to assure a part of the heat demand for space heating and in B2. The energy quantities are rather low due to the climate conditions, the limited size of the water tanks as well as the required temperatures (35°C for B1 and 45°C for B2). During summertime (no space heating needs), solar collectors connected to the ground are very active due to high incident radiation and lower storage temperature (around 20°C).

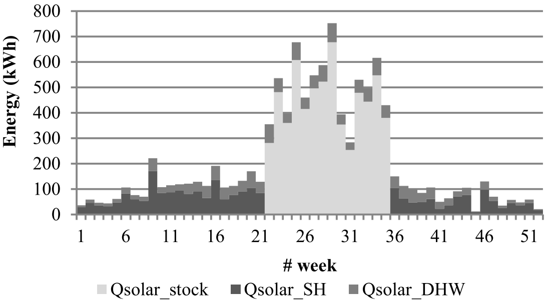


Figure 4: Solar production and storage

Heat production for space heating

Figure 5 shows the time distribution of heat that is sent to water tank B1 for space heating. This heat is either produced by the heat pump (indirect solar energy – $Q_{heatpump\_SH}$) or by solar collectors (direct solar energy – Q_{solar_SH}).

41.7% of the heat produced for space heating is covered by solar energy. The heat pump (which uses indirect solar energy) is the main producing device.

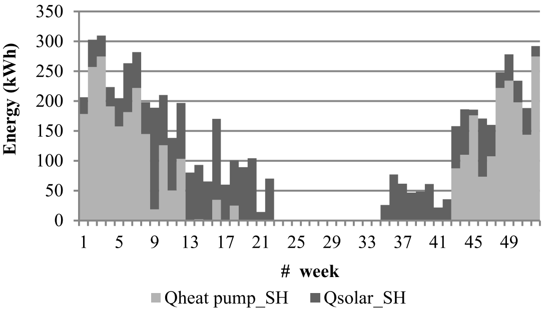


Figure 5: Heat production for space heating

Heat production for DHW production

The average value of heat that is stored in water tank B2 for DHW production is 38.9kWh/week. Figure 6 presents its time distribution as well as the contribution from the heat pump ($Q_{heatpump\_DHW}$) and the one from the solar system (Q_{solar_DHW}). Peak production for certain weeks correspond to a significant sunshine. The direct solar fraction for DHW production is more important than for space heating. It reaches 75.6%.

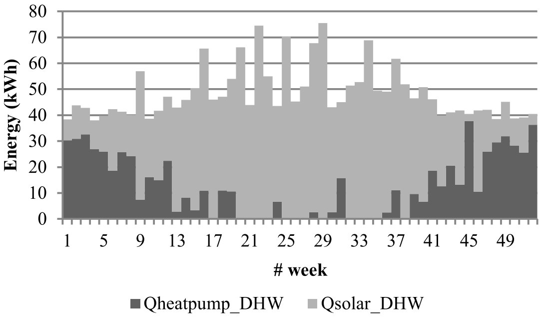


Figure 6: Heat production for DHW

Underground energy storage

Figure 7 shows the time distribution of the energy sent to the borehole energy storage and the time distribution of the energy that is recovered from the borehole energy storage thanks to the heat pump.

As previously mentioned underground heat storage occurs during summertime whereas its use by the heat pump occurs during wintertime. During the mid-season period, the heating needs (for space heating) can be nearly covered by direct solar heating. Solar energy is then stored in water tank B1 prior to its use and there is no need to run the heat pump. As a consequence, the underground storage is inactive (no storage and no heat recovery).

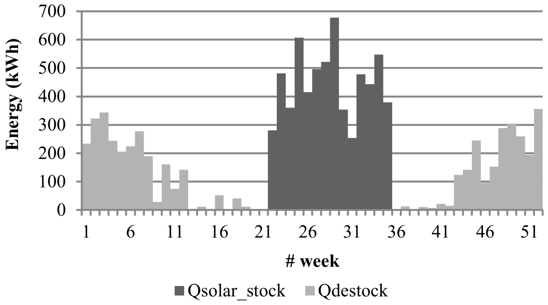


Figure 7: Ground energy storage and recovery

One-year energy performance

Table 4 presents the detailed energy performances for a one-year period. All energy data are given per square meter of heated surface. The efficiency of power plant has been taken equal to 0.40 for calculating the primary energy (non renewable part) consumption. Results are given for the system of interest and for the reference system.

Results show that the primary energy could be considerably reduced when using the system (9.44 kWh/m^2 instead of 39.40 kWh/m^2 for the reference system. The total heat quantity that is produced is 57.70 kWh/m^2 (system) and 54.85 kWh/m^2 (reference). The difference is mainly due to the heat losses that are more important when using storages (system). The low primary energy consumption of the system is mainly due to good solar coverages of both space heating and domestic hot water needs.

Sensitivity analysis

The main design parameters for such a system are the solar collector surface area (used for space heating) and the total borehole depth. Figure 8 presents the influence of the solar collector area on the heat pump SPF and the solar collector efficiency for a given borehole depth.

	Variable description	System	Reference
		kWh/m^2 or %	
$Q_{heatpump\_SH}$	Heat produced by the heat pump for space heating	23.29	36.18
Q_{solar_SH}	Heat produced by solar collectors for space heating (direct use)	16.63	/
Q_{losses_SH}	Heat losses in the space heating system	4.66	0.64
Q_{SH}	Heat distributed to the dwelling	35.26	37.18
W_{HP_SH}	Heat pump electricity consumption for space heating	3.19	10.41
SPF_{SH}	Heat pump SPF for space heating	7.30	3.50
$Q_{heatpump\_DHW}$	Heat produced by the heat pump for DHW preparation	4.33	18.67
Q_{solar_DHW}	Heat produced by solar collectors for DHW preparation	13.45	/
Q_{losses_DHW}	Heat losses in the DHW system	4.63	1.59
Q_{DHW}	Heat distributed through DHW system	13.15	17.08
W_{HP_DHW}	Heat pump electricity consumption for DHW preparation	0.59	5.35
SPF_{DHW}	Heat pump SPF for DHW preparation	7.40	3.50
$Q_{solar\_\_stock}$	Underground storage solar heat	34.44	/
$Q_{destock}$	Recovered underground heat	23.85	/
F_{solar_SH}	Solar coverage for space heating (based on produced heat)	41.70	/
F_{solar_DHW}	Solar coverage for DHW preparation (based on produced heat)	75.6	/
F_{solar}	Solar coverage of heat production (SH+DHW)	52.10	/
E_{prim}	Primary energy consumption	9.44	39.40
F_{renew}	Part of renewable in the heat production	83.6	28.10

Table 4: Comparison of energy performances: system and air to water heat pump without solar system (reference)

Figures 9 and 10 show the effect of solar collector surface area and borehole depth on the solar energy that can be stored in the ground and on the recovered solar energy (per square meter of heated surface).

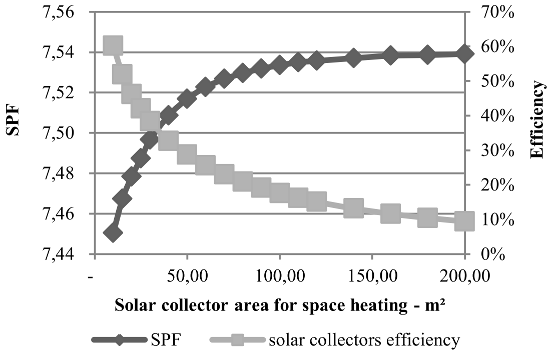


Figure 8: Effect of the solar collector surface area (for borehole depth equal to 150 m^2) on the HP SPF and solar collectors efficiency

Increasing the solar collector surface area for a given borehole depth allows for higher stored energy quantities (Figure 9). Lower recovered energy quantities are also observed (Figure 10) due to the fact that the direct solar contribution resulting from a higher solar collector surface area will reduce the heat pump contribution. As a consequence, higher average ground temperatures may be reached leading to higher SPF values but to lower solar collector efficiencies (Figure 8). For very high values of the surface collector area, the influence of a further increase on the quantity of energy that can be stored or recovered is low (Figure 9 and 10) and a value slightly above 20 m^2 seems to be adequate. Figure 8 shows that for such a value the heat pump SPF is already very high (compared to a geothermal heat pump without any solar storage) even if not located in the asymptotic part of the curve.

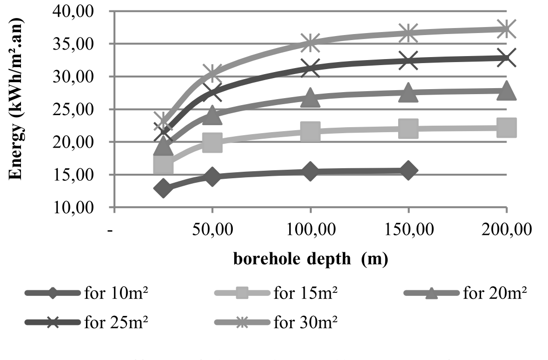


Figure 9: effect of the solar collector surface area and borehole depth on the stored energy

Increasing the size of the underground storage volume and heat exchanger has a positive effect of the energy storage process (Figure 9). The effect on energy recovery (Figure 10) is less important (lower HP source temperature but lower temperature difference between ground and evaporating fluid leading to a quite stable SPF and thus to a quite constant heat quantity that is transferred to the evaporator for a given heat quantity to be produced at the condenser.

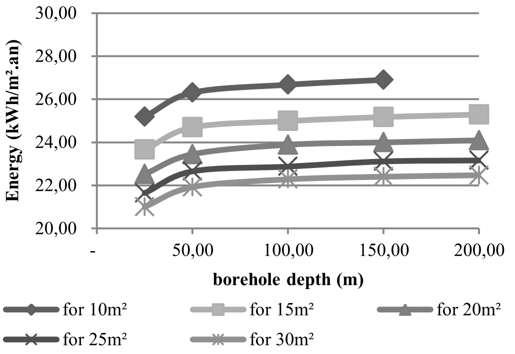


Figure 10: Effect of the solar collector surface area and borehole depth on the recovered energy

Figure 11 presents the primary energy consumption of the system as a function of the same parameters (as in Figures 9 and 10). It confirms the previous analysis: there is no optimum design (minimizing the primary energy consumption) and the asymptotic trend of the primary energy consumption as a function of both the solar collector surface area and total ground coupled heat exchanger length appeals for pragmatic choices. The selected design characteristics that leads to results presented in Table 4 may then be validated.

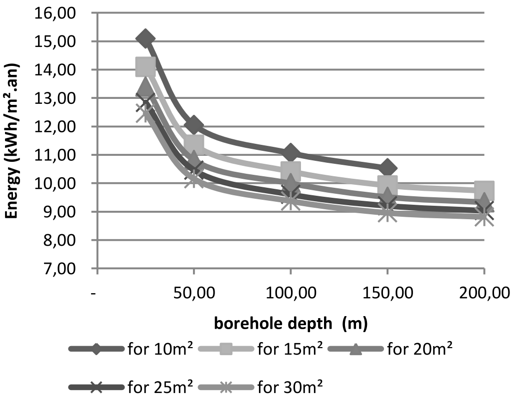


Figure 11: Effect of the solar collector surface area and borehole depth on the primary energy consumption

CONCLUSION

Using complex heat production systems that rely on technologies that are well known for their renewable contribution (solar collectors and high performance heat pumps) but coupled is such a way that both the direct solar contribution to heat production and the heat pump SPF are "maximized" may lead to important renewable contribution in the heat production (83.6%). Using an air to water heat pump without solar system (reference system) would have led to a renewable contribution of about 28.10% for space heating/domestic hot water production.

Such interesting system energy performances are reached by a combination of high solar coverage ratio (direct solar contribution: 41.7 % for space heating and 75.6% for DHW production) and high heat pump SPF due to source preheating that can be seen as an indirect partial solar contribution (assisted seasonal storage). Using solar energy for electricity production (for driving the heat pump) may be imagined so that the application could be net zero energy. Low electricity power is required so that the impact on the electricity grid would be reduced compared to lower SPF heat pump applications.

The proposed system may then be considered as an interesting solution for reaching ZEB targets with reduced impact on the energy production and distribution system. The impact of using it in all new buildings that are constructed within a year time in Belgium represents only a 0.07% reduction of the national primary energy consumption in the building sector.

The complexity of the system, namely due to the use of a short term and a long term heat storages, both being coupled with the heat pump, appeals for optimizing the design of each component taking into account their mutual effect on their working conditions. Lack of such design and integrated installation skills is one of the main restraint to the development of such systems.

The necessity to have heat pumps that are able to work properly with a low temperature lift between energy sink and source is another problem to be addressed.

Previous studies ([12], [13]) have shown that such solutions were not economically viable for a single building and should be considered for city districts. This study was conducted to improve the qualitative and quantitative knowledge about such complex systems under Belgian climate conditions and for building applications that correspond to the current Belgian regulation and state of the art. It aims at providing simple design rules to be used by stakeholders. It will be extended to city district applications and complemented to take into account auxiliary components energy consumption.

ACKNOWLEDGEMENT

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